LA-UR- 04-2566

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Submitted to: 15th Topical Conference on High-Temperature Plasma Diagnostics
19-22 April 2004
San Diego, California

Los Alamos
NATIONAL LABORATORY

The separatrix radius measurement of field-reversed configuration plasma in FRX-L

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Abstract

Magnetic pick-up coils and single turn flux loops are installed on the FRX-L device. The combination of the two measurements provides the excluded flux radius that approximates the separatrix radius of the field-reversed configuration plasma. Arrays of similar probes are used to map out local magnetic field dynamics beyond both ends of the theta-coil confinement region to help understand the effects of cusp locations on flux trapping during the FRC formation process. Details on the probe design and system calibrations are presented. The overall system calibration of excluded flux radius measurement is examined by replacing FRC plasma with a known radius aluminum conductor cylinder.

I. INTRODUCTION

In Field-reversed Configuration (FRC) plasma research, magnetic pick-up coils (magnetic probes) and magnetic flux loops are the key diagnostics. The probes measure the local time-varying external magnetic field B_e, and a usually single-turn wire loop inside flux-conserving conductor (theta coil) measures the excluded magnetic flux ($\Delta\Phi$) due to the FRC plasma diamagnetism. The radius of FRC plasma at the location of the measurements (the FRC's separatrix radius r_s) is approximated by the directly measured excluded flux radius, $r_{\Delta\Phi}=(\Delta\Phi/\pi B_e)^{1/2}$. Arrays of probes and flux loops measurements at different axial locations (z) allow one to approximate the FRC plasma shape. When these results are combined with line-integrated density, some other key parameters of FRC plasma can be estimated, such as average β, total temperature of plasma, and plasma confinement properties[1,2].

The goal of the Field-Reversed configuration eXpeiment with a Liner (FRX-L) at Los Alamos National Laboratory is to produce a target plasma with plasma density at $\sim 10^{23}\mathrm{m}^{-3}$, lifetime at 10-20$\mu$s, and total temperature around 400eV. This target plasma will then be translated into a flux conserver, which is a conducting cylinder, called a liner. The liner with the FRC plasma trapped inside will be adiabatically compressed eventually to fusion relevant plasma conditions[3]. Diagnostics implementation in such devices is difficult because of the strong-pulsed electromagnetic environment, mechanical vibrations and shocks, and especially the very limited diagnostic accessibility[4].

Figure1 shows a schematic view of FRX-L device. The main vacuum chamber is a 10.5cm internal diameter quartz tube with a thickness of 2.5mm and total length ~ 70cm. The aluminum single-turn theta coil is sliced into four segments spaced apart by 1cm slots to provide accessibility for diagnostics. The theta coil segments cover the quartz tube by almost half of its length (36cm). Beyond each end of theta coil, stacked pancake coils (cusp/mirror coils) are stationed 7cm away. A stainless steel plate (flux excluder) of 1cm thickness sits between the cusp coil and theta coil to minimize the mutual inductance between the coils. The coordinates in the system are defined naturally as z-direction along coil axis, radial and poloidal (theta) directions. During normal operation, with a precisely programmed control sequence, a 10kV/10kA bias capacitor bank, a 60kV preionization (PI) bank and 120KV/1.5MA (it is usually fired at 70KV now) main banks discharge through the theta coil; the10KV/10kA cusp bank discharges through both ends of the cusp coils. The temporal history of local fields inside the theta coil segments and the topology of fields between cusp coils and theta coil are of particular interest in terms of guiding the machine operation and characterizing the plasma properties.

16 magnetic probes are installed on the four segments of theta coil, which give us ~2cm axial resolution of the local magnetic field in the theta coil confinement region. Four single-turn wire loops are looped around the quartz tube underneath each theta coil segment. The measurements from these probes and loops derive the FRC plasma volume and shape. 3 pairs of magnetic probes, each is consisted of one B_z probe and one B_r probe, are installed on a polyethylene holder seating between the stainless steel plate and the west end of theta coil to map the two-dimension topology of field lines in the region (cusp region). Details on the fabrication of the diagnostics and calibration methods are presented in the following.

II. Magnetic flux measurement

The flux loop diagnostic is straightforward. Based on Faraday's law, the integration of the output voltage of the wire loop is the magnetic flux that passes the wire loop. With a simple RC passive integrator, a digitizer will record the measured flux directly.

Figure 2 is the effective electric circuit of the flux measurement diagnostics. The internal resistance of the wire loop and parasitic capacitance are neglected comparing with the values of the showing components in the interested frequency range (~ 250kHz) in the circuit, The flux loop wire is a Silicone Coated insulation copper wire (Wiremax SK 3020A), rated at 30kV DC and 200°C; its insulation is resistant to ozone and ultraviolet degradation, which are necessary properties because of plasma light emission and occasional arcing around the quartz tube. The estimated output peak voltage from the loop is ~12kV. The temperature of the quartz tube wall may rise to much higher than 200°C in plasma shot, but since the plasma pulse is just about 20μs, and the wire has very high heat capacity, we did not see any damage to the wire; however, Kapton® tape does burn in this region. The wire loops around the quartz tube and the leads are immediately closely twisted all the way to a shielded high voltage divider.

The high voltage divider is composed of resistors R1 (68Ω×15), R2 (13Ω), and R3 (68Ω×15), they are in series and caged inside a copper tube filled with UX9156 Urethane elastomer (Lord Corporation). The output voltage across R3 is sent to another divider (power divider) through 100 ft of RG223/U BNC cable, which splits the signals further into two branches: one is fed into an RC integrator/digitizer to be recorded as directly measured flux, the other is fed into a subtraction circuit to be subtracted from probe signal to give a direct measurement of FRC plasma diamagnetism (the excluded flux of the FRC plasma). The high voltage copper shield enclosure is connected to the outer layer of main screen room by copper braid that screens the long BNC cable. The digitizers inside screen room are grounded to the inner layer of the screen room and the inner layer is then single-point grounded to the outer layer of the screen room. At 250kHz, which is a frequency close to PI bank and main bank discharging modulation frequencies, the voltage divider's factor (together with the long cable) is 317, and after a simple passive RC integrator of RC~200μs, the resulting peak voltage that goes into a digitizer of 1MΩ input resistance is about 0.5V.

III. Magnetic probe design

A comprehensive discussion on magnetic probe design on plasma devices can be found in *Plasma Diagnostic Techniques*[5]. Two kinds of probe with different jacket materials are developed in FRX-L. One type is with glass tubing jacket. The probe is inserted into a through hole on the theta coil segment, and rested on the quartz tube outer wall; the other type is with heat shrinkable plastic tubing jacket, it is installed between stainless steel plate and west end of theta coil to map out the magnetic field topology in the cusp region.

In order to measure the magnetic fields between the quartz tube outer wall and inner side of theta coil (i.e. the external field of the FRC, B_e), small holes of diameter of 4.6mm were drilled through the theta coil segments to accept magnetic probes. The number of holes and their diameters were minimized to reduce magnetic filed perturbation in the theta coil confinement region. During a shot, the theta coil segments are at several tens kV and the probes are grounded at the screen room ground. So probes must be small, rigid and with very good insulation jacket.

The effective circuit of magnetic probe measurement is very similar to the flux measurement circuit as shown in figure 2, except that there is no high voltage divider (R1, R2 and R3) in the circuit. Both the probe and flux loop signals are split into two ways. One way is integrated and recorded as the local magnetic field; the other way is fed into an excluded flux subtraction circuit to work with flux signal to get the direct excluded flux measurement. The total effective area of the probe needs to be $\sim 3\times10^{-5}m^2$ (taking RC~200μs, B_e~3Tesla with 2.5μs rising time, the signal amplitude is ~36V), in order to match the flux signal in the subtraction circuit. This is done by winding 36AWG (#36 Beldsol™ magnet wire, Belden) on a Φ1.8mm×2.5mm Teflon® tubing form for 12 turns. The turn-to-turn voltage drop is about several volts. For quite a long time, SureHold® super glue was applied onto the coil core to fix the coil windings, but the glue turned out to deteriorate the insulation layers of Beldsol™ wire due to its "biting into plastic" ability, which failed the coil's turn-to-turn insulation occasionally (one probe may survive only tens of main bank shots). Due to this reason, we have been reluctant to twist the leads to reduce extra coil area before the transition to BNC connector (Kings KC-59-162). Instead, one lead is soldered to a Teflon® wire of 30AWG (Alphawire) that runs inside a copper tubing (diameter 2.4mm, length 19cm) and then is soldered to the pin of the BNC connector, the other lead is immediately soldered to the copper tubing which is connected to the ground of BNC connector at the other end. The coil core, the Teflon wire, the copper tubing and sections of Teflon® tubing spacers all are epoxy glued together relatively to form a probe stick, then this probe stick is inserted into a glass tubing jacket (Φ4.0mm×17.5cm) and is epoxy glued to the glass.

There were two problems associated with the design. One is the turn-to-turn failure; the other is the frequency response variation of the effective coil area, which is about ±3% of the average value in 100 ~ 400 kHZ. We solved the first problem by replacing superglue with epoxy to fix coil windings. It proved to be very effective, as the probes have already survived hundreds main bank shots. The second problem is basically due to the co-axial probe structure, that makes the probe's total inductance tens times much bigger than its coil solenoid inductance (~180nH). We are making a prototype of probe where we bring the twisted Teflon® wires that are soldered to the probe's leads to a BNC connector, which eliminates the co-axial structure of using copper tubing as ground return path. This probe design is undergoing testing.

Several jacket insulation materials have been tested and compared such as layers of Kapton® tape, heat shrink tubing, Tygon tubing and glass tubing. Finally, glass tubing is chosen because of its rigidity, reliable insulation property and resistance to ultraviolet and ozone that come from either plasma or occasional air arcing in the region. After FRX-L was mechanically reinforced recently to reduce mechanical vibrations during discharging, the survivability of the magnetic probes with glass jacket is improved significantly.

Probes that are used to map out cusp region magnetic fields basically share the same design as detailed above, except that the probes are jacketed with a double layer of heat shrinkable tubing to provide a little bit more flexibility to accommodate the stronger vibrations caused by firing cusp coils in that region.

IV. Calibrations

As shown in Figure 2, the magnetic field measurement and excluded flux measurement system are composed of probes (flux loops), voltage dividers, long BNC cables and simple passive RC integrators. Each of these parts needs to be calibrated.

A solenoid coil calibrator of Φ20mm is set up to calibrate probe's effective area. The magnetic field inside the calibrator is calibrated by a Hall probe (LakeShore Model 450), and the factor is 28.83Gauss/A. With a current probe (Tektronix A6302 Current Probe with AM 503 Current Probe Amplifier) to measure the current that runs through the solenoid, a magnetic probe's effective area can be measured along with the frequency. We usually average the areas at frequencies of the interested range to obtain effective probe area.

The voltage dividers and cables are also calibrated at the frequency of interest.

Passive RC integrators are used to perform signal integrations to give us direct readout of magnetic fields and fluxes. In FRX-L, the local field or flux is the superposition of different time scale fields, which are cusp field of quarter cycle time $t_{1/4}$ ~170μs, bias field of $t_{1/4}$ ~148μs, PI field of $t_{1/4}$ ~1μs and main bank field of $t_{1/4}$ ~1.3μs; thus a compromise is made to choose integration time constant at the order of data recording time with R~20kΩ, C~10nF, RC~200μs. This results in the fact that integration droop correction must be considered, which requires not only an accurate calibration of integration constant, but also a droop correction constant for each RC integrator.

Again in Figure 2, the output of integrated voltage across the capacitor C is

$$V_0 = \frac{1}{RC}\int V_i dt - \frac{1}{(R//R_L)C}\int V_o dt$$

where V_i is the input voltage into the integrator; product RC is the integration time τ and the denominator in the second term $(R//R_L)C$ is the droop constant τ_D of the RC integrator ($R//R_L$ means resistor R and the load resistance R_L are in parallel). In the FRX-L data acquisition program, all the fields and flux measurements are corrected based on the above formula.

In order to accurately determine the integrator's integration and droop constants, we developed a curve fit procedure, which we believe gives us ~ 0.5% accuracy of the constants. A single square pulse of amplitude V_i, pulse width T is applied to the RC integrator; a digital oscilloscope records both the input (V_i) and output (V_o); and then we change τ and τ_D to make the integration of the above formula fit the real output V_o by the least square curve fit procedure[6]. The criterion to stop the fitting process is to determine the minimum χ^2 in the designated range of τ and τ_D, which are ± 0.25RC for τ, and RC-0.25RC for the τ_D, where RC is the nominal value of the integrator. It is noticed that the fitting gives very reproducible values when several trials are done. τ and τ_D would be stabilized after the input pulse width T>9RC. In the worst case, the error of τ and τ_D are within ~0.5% of the averaged values after T>9RC, when T~18RC.

Having done the calibrations for each part of the system as discussed above, the whole magnetic field and excluded flux measurement system is verified by replacing FRC plasma with an aluminum cylinder of diameter 6.38cm, length 100cm inside the quartz tube. Based on $r_{\Delta\Phi}=(\Delta\Phi/\pi B_e)^{1/2}$, the measured excluded flux radius $r_{\Delta\Phi}$ is between 3.2 to 3.5cm at four segments of theta coil; and at the middle plane of the theta coil, the error is about 1.9% from the nominal radius of the aluminum cylinder.

V. Measurement results and discussions

Figure 3 shows part of the measurement results in a typical FRC plasma shot on FRX-L. The magnetic field has very slow change (-300μs to 0μs) and very quick variations (after 0μs), however, it is the field change after 0μs that matters in the study, so every calibration is done at the fast time scale. The FRC plasma is about 3cm in radius and lasts about 18 μs.

Since the integrator's constant RC is chosen shorter than the total data recording time, even data bit noise may affect the measurements due to droop correction procedure, thus it is highly desirable to deploy 10 bit or 12 bit digitizers to record the signals rather than use the current 8 bit digital oscilloscopes. Meanwhile, the grounding system should be carefully examined as we discussed in Section II.

Change the probe's co-axial structure to twisted wire to bring out the probe signal may improve probe's frequency response and may also lead to better system measurement accuracy. Although the BNC cable RG223/U is rated usually 1400VDC to 1900VDC, we found that it is very effective and useful to check the cable's voltage standoff at 2500V with a high voltage ohmmeter (Megger™ Testing Set, Series 1).

This work is supported by DOE-OFES Contract No. W-7405-ENG-36.

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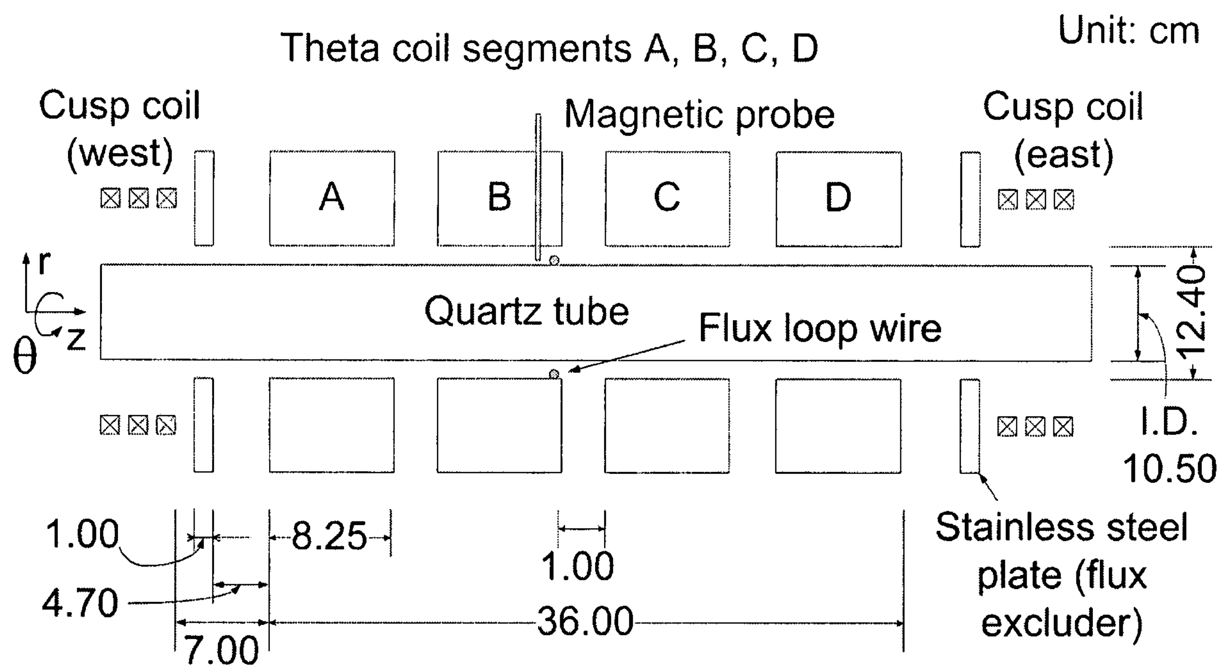

Fig.1. Schematic cut view of FRX-L device. Shown are the main dimensions of the coil installations and vacuum chamber. A magnetic probe and a flux loop wire are also shown. 16 axial probes (B_z) are installed on the theta coil segments; 4 flux loops loop around the quartz tube underneath each of the theta coil segment; and 3 pairs of axial probes (B_z) and radial probes (B_r) are installed on a polyethylene holder between the west cusp coils and theta coil segment A.

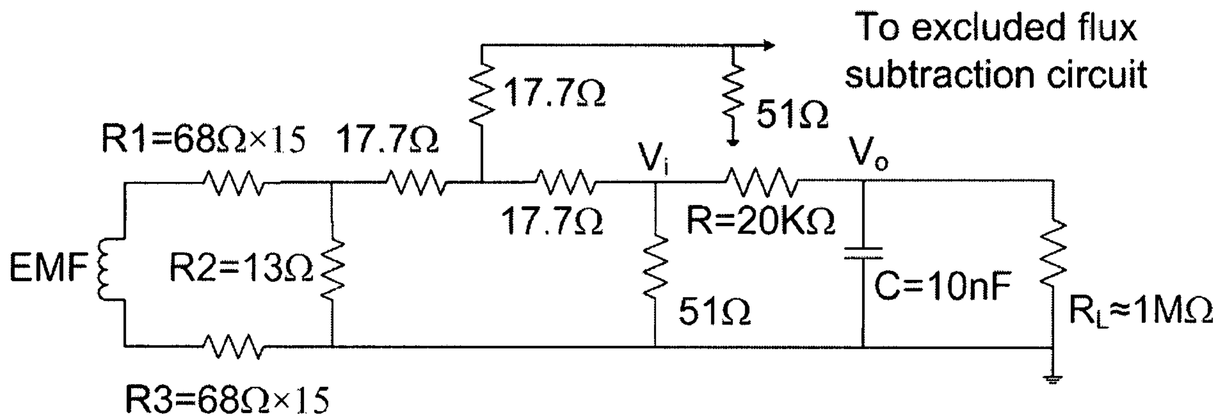

Fig. 2. The effective circuit of the magnetic flux measurement system. EMF in the circuit is the induced voltage of flux loop. When removing the high voltage divider (resistors of R1, R2 and R3), and directly connecting the EMF from a magnetic probe's output to the remaining circuit, it will be the effective circuit for magnetic probe measurement system.

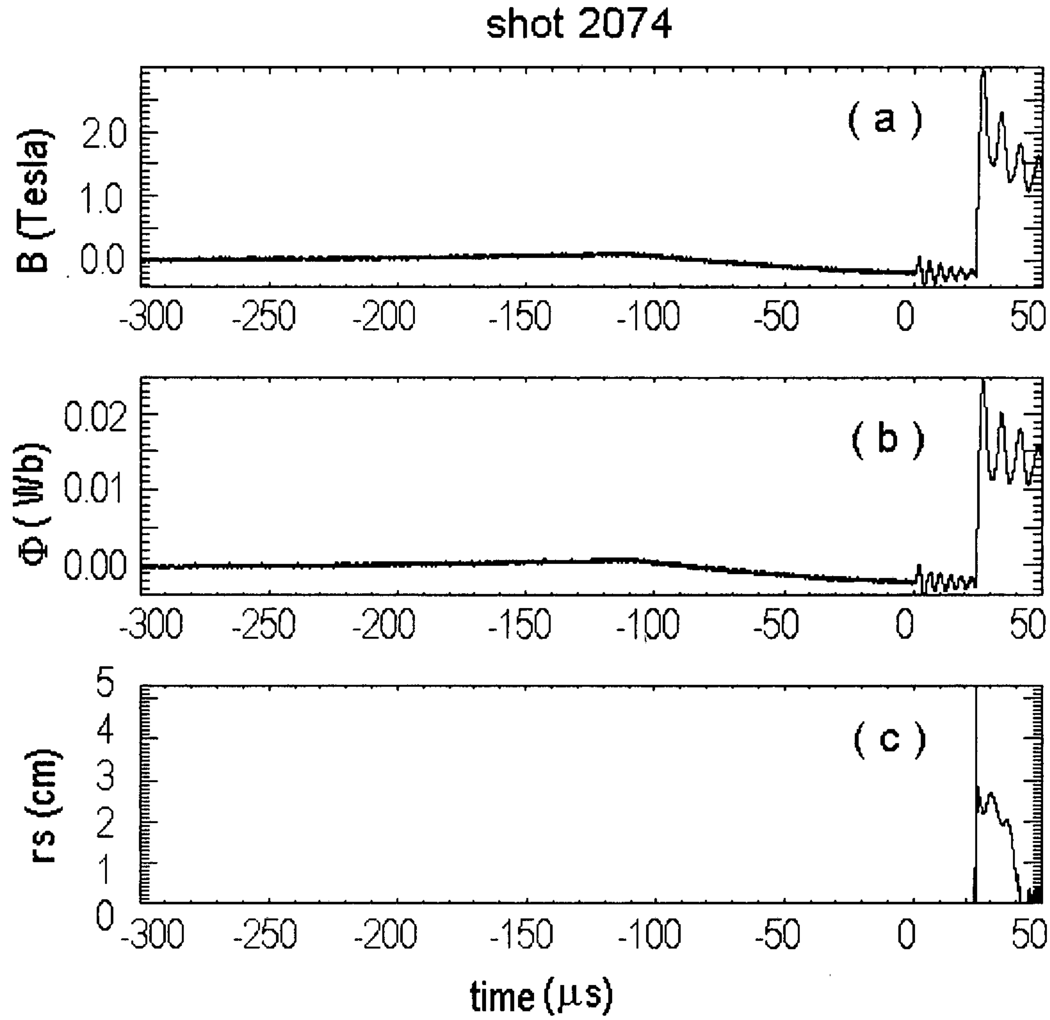

Fig. 3. (a) Measurement of local axial magnetic field by a probe at the middle-plane of theta coil. (b) The measured magnetic flux at the middle-plane of theta coil. (c) Calculated excluded flux radius from the magnetic field and flux measurements approximates the separatrix radius of the FRC plasma. The FRC plasma is about 2.8cm in radius at the middle plane of theta confinement region during its equilibrium (~30μs)